

Population Gradients in Local Group Dwarf Spheroidals

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ABSTRACT

We present a systematic and homogeneous analysis of population gradients for the Local Group dwarf spheroidals (dSphs) Carina, Sculptor, Sextans, Tucana, Andromeda I-III, V, and VI. For all of the Milky Way companions studied here we find significant population gradients. The same is true for the remote dSph Tucana located at the outskirts of the LG. Among the M31 dSph companions only Andromeda I and VI show obvious gradients. In all cases where a HB morphology gradient is visible, the red HB stars are more centrally concentrated. The occurrence of a HB morphological gradient shows a correlation with a morphology gradient in the red giant branch. It seems likely that metallicity is the driver of the gradients in Sextans, Sculptor, Tucana, and Andromeda VI, while age is an important factor in Carina. We find no evidence that the vicinity of a nearby massive spiral galaxy influences the formation of the population gradients.

Subject headings: galaxies: dwarf – galaxies: structure – galaxies: stellar content – stars: abundances – stars: horizontal-branch – Local Group

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1. Motivation

Dwarf spheroidal (dSph) galaxies contribute to the faint end of the galaxy luminosity function and may be basic building blocks in hierarchical galaxy formation scenarios. In all Local Group (LG) dSphs an old stellar population ($\text{age} \geq 10$ Gyr) exists as indicated by the presence of a horizontal branch (HB). The HBs of the dSphs mostly show a bimodal morphology, i.e., both the blue and the red part of the HB are populated. Over the last few years it has become clear that these apparently simple galaxies actually show a large range of metallicities as well as star to star variations in elemental abundance ratios, indicating that dSphs have experienced a complicated star formation history with various self enrichment processes (Mighell & Rich 1996; Hurley-Keller, Mateo, & Nemec 1998; Gallart et al. 1999; Dolphin 2001; Shetrone, Côté & Sargent 2001).

For a few LG dSphs radial gradients in the HB morphology have been reported (e.g., Da Costa et al. 1996; Hurley-Keller, Mateo, & Grebel 1999). In each case the blue HB (BHB) stars have a more extended distribution than the red HB (RHB) stars.

Population gradients are well known for some dwarf irregular (dIrr) galaxies with ongoing star formation, e.g., Sextans A, WLM, Leo A, and IC 1613 as summarized by Grebel (1999). While high-mass dwarf galaxies, e.g. the LMC, tend to show widespread, multiple zones of concurrent star formation, low-mass dwarf galaxies ($10^7 M_{\odot}$) show centrally concentrated younger populations (Grebel 2000). In particular the transition type dIrr/dSph galaxy Phoenix and the dSph Fornax show a central concentration of the younger stars (Martínez-Delgado, Gallart & Aparicio 1999; Stetson, Hesser, & Smecker-Hane 1998).

Radial gradients in the HB morphology can be interpreted as an imprint of the ancient formation process of the dSphs and may help to distinguish different formation scenarios. In this paper we perform a homogeneous study of HB morphology gradients for a large sample of dSphs in the Local Group. We analyze the spatial distribution of BHB and RHB stars, the red giant branch (RGB) stars, and, if present, of red clump (RC) stars of LG dSphs.

2. The horizontal branch as a tracer of population gradients

A HB forms in stellar populations older than ~ 10 Gyr and consists of He core burning stars. BHB stars lie blueward of the RR Lyrae strip, while the RHB stars have lower surface temperatures and lie redwards of the instability strip. The first parameter governing the HB morphology of a population is metallicity: Metal rich populations tend to form a red HB, while metal poor populations in general form blue HBs. However, globular clusters with the same metallicity may exhibit very different HB morphologies, demonstrating that additional parameters play a role. For instance, differences in age on a time scale of a few Gyr can have a significant influence on the HB morphology (Sarajedini, Chaboyer, & Demarque 1997). For a fixed metallicity the HB morphology can change from a completely red HB to an entirely blue HB for population ages between 11 Gyr and

15 Gyr (Lee, Demarque, & Zinn 1994; Lee et al. 2001). Populations with ages between 1 and 10 Gyr form an RC instead of a HB (Girardi et al. 1998). A red clump is indeed the continuation of the sequence of core He-burning stars, but is formed by stars with higher total masses. The existence of an RC therefore is a tracer of intermediate age stellar populations in a galaxy. Consequently, the existence of spatial variations in the distribution of core He-burning stars (RHB, BHB, and RC) can reflect either age or metallicity differences, or a mixture of both. Other parameters may still play a rôle. For example, the old, metal rich open cluster NGC 6791 contains a population of stars on the extended blue HB in addition to its expected red HB (Kaluzny & Udalski 1992; Liebert, Saffer, & Green 1994).

In an attempt to separate the effects of age and metallicity, we also will consider variations in the RGB morphology. For a given age, a lower metallicity results in a bluer RGB. A decrease in age has a similar effect (age-metallicity degeneracy). We demonstrate this effect in Fig. 1 where we show isochrones (Girardi et al. 2000) for $z = 0.004$ and $z = 0.0004$ for ages of 10, and 14 Gyr. Note that for ages larger than 6 Gyr the effect of age on the RGB morphology is nearly negligible.

3. Data sample and reduction

The LG contains 17 currently known dSphs. We consider here 3 of the 9 Milky Way companions, namely Carina, Sculptor, and Sextans, and 5 of the 6 Andromeda dSphs, Andromeda I-III, V, and VI. In addition we analyze the isolated dSph Tucana. Our sample is restricted to those galaxies for which deep, wide-field data are available to us. To study the distribution of the blue and red HB stars, observations of a sufficiently large field and deep photometry are required. We present results from our own observations as well as data from the Hubble Space Telescope (HST) archive. The data sources of our sample are summarized in Tab. 1, including the instrument used, filter set, and radius covered, and references where available. We show in Fig. 2 the observed field of view for each dSph on a Digital Sky Survey image.

All HST observations (the five Andromeda dSphs and Tucana; see Tab. 1) were reduced using HSTphot (Dolphin 2000a). This program performs point spread function photometry on Wide Field Planetary Camera 2 (WFPC2) (Trauger 1994) observations with PSFs based loosely on Tiny Tim models (Krist 1993). It carries out corrections for charge transfer efficiency effects and performs the photometric calibration and transformation to the Johnson photometric system (Dolphin 2000b). The photometry of the five Andromeda dSphs and Tucana were dereddened according to the extinction maps of Schlegel, Finkbeiner, & Davis (1997). The Andromeda dSphs were observed with the F450W and F550W filters. Da Costa et al. (2000) mention that the zeropoint for the conversion from the F450W filter to Johnson B should be corrected by 0.055 mag. This correction was applied to the $B - V$ color of the Andromeda photometry, leading to slightly redder colors.

The ground based observations were reduced using the IRAF¹² standard CCD reductions and the **daophot** package (Stetson 1992) running under IRAF.

Details of the CTIO 4m BTC reductions of Sculptor can be found in Hurley-Keller, Mateo, & Grebel (1999). The data obtained with the Mosaic 2 camera for Sextans will be discussed in Harbeck et al. (2001). Details of the reduction of the CTIO 1.5m data of Carina will be described in Grebel et al. (2001).

The color magnitude diagrams (CMD) for the LG dSphs are shown in Fig. 3.

4. Analysis

To investigate the presence of a possible radial HB morphology gradient for a given dSph we select the blue HB and red HB from the CMD according to the selection boxes in Fig. 3. The observations for the dSphs were made using different filter combinations, therefore the color- and magnitude selection vary for the galaxies. Even in the case of the five Andromeda dSphs, which were all observed in the same filters, the HB morphology varies significantly. Due to different contamination of the red HB by the RGB we define the best selection criteria for each individual galaxy to minimize contamination effects. A more quantitative analysis that corrects for this contamination of the HB is performed in section 7. The red edge of the BHB selection box and the blue edge of the RHB box are chosen to avoid stars from the instability strip. The boundaries of the instability strip in the different filter sets are: $B - V = 0.18$ to 0.4 (Sandage 1990); $V - I = 0.4$ to 0.75 ; $C - T_1 = 0.38$ to 0.64 (Harbeck et al. 2001); $B - R = 0.35$ to 0.75 (based on visual inspection of Sculptor’s CMD). In the case of Carina, where a red clump population is visible, we select this region from the CMD to compare its spatial distribution with that of the RHB.

Most of the dSphs in our sample have a non negligible ellipticity $1 - \frac{b}{a}$ as listed in Tab. 1. Considering just the radial distance \tilde{r} of a star to the center of its galaxy would ignore this ellipticity and weaken any gradient effects. We therefore calculate for each star an ellipticity corrected distance r , equivalent to the major half axis. In the following we will always use this corrected distance when talking about radial distances to a galaxy center. The centers and position angles for the dSphs were chosen from published work, as referenced in Table 1. While different populations may exhibit different centroids (Stetson, Hesser, & Smecker-Hane 1997), the offsets are small. We therefore search for possible gradients in old and intermediate-age populations by assuming azimuthal symmetry.

We use several different tools to analyze the radial distribution of different populations:

¹²IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

4.1. Cumulative radial distribution

We plot the cumulative radial distribution of the BHB, RHB, and, if present, the RC stars. We then apply a Kolmogorov-Smirnov (K-S) test to the radial cumulative distributions, which gives the probability of whether the distributions of the BHB and RHB stars are drawn from the same population.

4.2. T_2 statistics of number ratios

We use the number ratio

$$N_{HB} = \frac{n_{BHB}}{n_{BHB} + n_{RHB}} \quad (1)$$

which measures the blueness of the HB (Mironov 1972). N_{HB} varies between 0 for a completely red HB and 1 for a totally blue HB. N_{HB} is calculated for radial bins with the width of a core radius each. We overplot N_{HB} for the individual bins in the cumulative distribution diagrams as histogram bars (Fig. 5). If more than two core radii are covered by the observations this method shows whether there is a trend in the morphological gradient or just a local fluctuation. We also calculate N_{HB} for all stars with a radial distance larger than a single core radius. We refer to this radial selection as the “outer region”, while all stars within a core radius belong to the “inner region”. For Carina this analysis is also carried out to compare the distribution of the RHB and the RC stars.

T_2 statistics, which quantify the probability that two number ratios are derived from the same distribution (Da Costa et al. 1996), is then performed on the two N_{HB} values in the inner and outer region. The T_2 value has a normal distribution around zero with a width of one if the two compared number ratios are derived from the same distribution. T_2 values therefore directly measure at what σ -level two distributions are distinct. During the analysis it turned out that the T_2 -significance of an existing gradient is strongly influenced by the selection of the radii within which N_{HB} is calculated. We therefore decided to separate the inner and outer bin at the core radius for all dSphs to have a unique criterion, even though one could easily tune up the T_2 -significance by individual bin selections for each dSph.

We also define the gradient strength parameter

$$S[HB] = \frac{N_{HB}(r \leq r_c)}{N_{HB}(r \geq r_c)}. \quad (2)$$

$S[HB]$ compares the blueness of the HB in the inner and outer part of a dSph, separated by the core radius, and is therefore a measure for the strength of a morphology gradient on the scale length of a core radius. $S[HB] = 1$ for a homogeneous morphology without any gradients. $S[HB] < 1$ indicates a concentration of red HB stars, while $S[HB] > 1$ for a concentration of the BHB stars. We define $S[RC]$ in the same manner to compare the RC with the RHB.

4.3. RGB radial distribution and metallicities

We fit the mean ridge lines of the red giant branches (RGB) for all the galaxies by a third order polynomial. This divides the RGB in a red and a blue population (RRGB and BRGB). This ridge line is shifted in the color direction to envelope the red and blue part of the RGB as shown in Fig. 3. We tried to include as much of the RGB in this selection as possible and to avoid field star contamination. The same analysis as described for the HB stars is then applied to the RGB stars.

4.4. The HB morphology index

We determine the HB morphology index

$$\frac{B - R}{B + V + R}$$

(Zinn 1986). B, R, and V are the numbers of blue, red, and variable stars in the HB, respectively. The determination of this index is simple in the case of Sculptor, but becomes more complicated for Sextans due to the field star contamination of the RHB. The HB of the distant Andromeda companions and Tucana merges with the RGB, and the number of RHB stars cannot be measured directly. Since we need absolute numbers of red HB stars to compare the HB morphologies of the dSphs we need to correct for this contamination: The luminosity function (LF) is plotted for all stars redder than the red end of the instability strip (considered to be at $B-V=0.4$; $V-I=0.8$), as demonstrated in Fig. 4. The HB is a clearly distinct peak above the continuum of the RGB LF. We describe the LF of the RGB at the luminosity of the HB by a linear function and subtract this from the whole LF. Counting the remaining stars gives us a good estimate for the correct number of red HB stars. The same method is used to correct for the field star contamination in Sextans' HB, but with an additional cut at the red end of the RHB. The HB morphology index is determined for (i) the whole field covered, (ii) for radial bins with the width of the core radius, and (iii) for the inner and outer bins.

5. Radial gradients in the HB morphologies

The radial cumulative distributions of the He core burning stars in our dSphs are drawn in Fig. 5 with solid lines for the RHB stars and with dashed lines for the BHB stars. The histogram bars show the N_{HB} values as a measurement of the HB morphology for radial bins with the width of one core radius, while the thick bars show N_{HB} for all stars outside the core radius.

The corresponding statistical values (K-S-Test, T_2 , and S) are listed in Tab. 2. For Carina the results of the comparison between the RC and the RHB are listed as well.

5.1. The Milky Way companions

Due to the large angular extent of the nearby galaxies we have a strong contamination with foreground stars, especially in Carina and Sextans. Ratnatunga & Bahcall (1985) estimate the expected field star contamination for the globular cluster Pal 3, which is close to Sextans, to be ~ 9.4 stars in a ± 1 magnitude bin per arcmin² at the HB magnitude of Sextans. In contrast, for Sculptor we expect only 1.3 stars per arcmin². As can be seen in the CMDs, this contamination affects only the RHB and RC number counts, which will be overestimated. The foreground objects have a uniform distribution and therefore let the contaminated RHB and RC star sample appear less concentrated than they actually are. The gradient strengths determined here for the MW companions are therefore lower limits.

All three Milky Way companions considered here have different HB morphologies. Carina is the only one to show a prominent red clump. All three show strong radial population gradients in the morphology of the He-core burning star distribution.

The **Carina** dSph shows no significant gradient in its HB morphology: The K-S-probability that the RHB and BHB stars have the same radial distribution is 43 percent; the T_2 value of 0.13 is consistent with an equal distribution of RHB and BHB stars, as well. But the RC stars show a very significant central concentration compared to the HB. Such a concentration of the younger populations was already suggested by Mighell (1997).

Sculptor has the most significant HB morphology gradient in our sample, as indicated by the high T_2 -value of 6.2 and a K-S-test result of $1.8 \cdot 10^{-6}$. This result confirms the finding of Hurley-Keller, Mateo, & Grebel (1999), based on the same data, and that of Majewski et al. (1999), who use independent observations. Care has to be taken when interpreting the K-S test result due to the properties of the observations with the BTC camera; this camera is a mosaic of 4 chips with 5.4 arcmin gaps. These gaps are smeared out by the elliptical distribution of the stars. But one should keep in mind that the K-S test is strictly defined for contiguous distributions only.

The HB morphology gradient in **Sextans** is not as significant as compared to Carina or Sculptor due to lower number statistics of the sparse blue HB. But with $S = 0.57$ and $T_2 = 2.6$ its gradient is still very strong.

5.2. The Andromeda companions

The expected field star contamination towards Andromeda is ~ 5.6 stars per arcmin² in a ± 1 magnitude bin for the HB luminosities. But due to the smaller apparent angular size of the Andromeda dSphs, field star contamination does not play a major role for the M 31 dSph gradients.

The M 31 dSphs show a variety of population gradients. **Andromeda I** seems to show a strong radial HB morphology gradient: While the result of the K-S-test is consistent with no gradient,

the result of the $T_2 = 2.6$ and $S = 0.37$ formally suggest a very strong gradient. This is consistent with the result of Da Costa et al. (1996), whose work is based on the same data we used. But the result for the outer bin is based on only 25 stars. This suggests that the HB gradient may become more pronounced beyond the field covered by HST and our result for Andromeda I is not reliable. A larger field coverage would be desirable to clearly establish the existence of a gradient, but no such data exist at present.

Andromeda II does not show a significant gradient (K-S-test: 22%, $T_2 = 1.2$). This result is again consistent with the work of Da Costa et al. (2000). In **Andromeda III** there is no obvious gradient (K-S-test: 33%, $T_2 = 0.9$) either.

The plot of the HB star distribution in **Andromeda V** in Fig. 5 suggests a central concentration of the red HB stars. But the distributions of BHB and RHB stars are still consistent with being similar (K-S-test: 24%, $T_2 = 0.7$).

Finally, in **Andromeda VI** there is a significant HB gradient (K-S-test: 0.1%, $T_2 : 2.7$).

5.3. The lonesome Tucana

Tucana has a very strong HB morphology gradient ($S = 0.54$) at a high significance level (K-S-test: $5 \cdot 10^{-4}\%$, $T_2 = 4.4$). While all of the other nine dSphs are presumably bound to a massive spiral galaxy, Tucana appears to be isolated within the LG. If Tucana has always maintained a large distance from massive galaxies it would be an example of undisturbed evolution in a dSph. If a HB gradient can form in such an isolated environment, this may indicate that it is created through internal processes in dSphs (Grebel 2000).

6. Metallicity gradients in dSphs seen in the RGB

We analyzed the radial distribution of the red and blue part of the RGB as described in the Section 4.3. For Carina the contamination of the RGB by field stars is extremely high, and there is no comparison field for statistical field star subtraction available. It is therefore impossible to make a sensible analysis of possible gradients: Small variations in the selection criterion for the RRGB and BRGB can produce any desired gradient in the RGB morphology. We therefore ignore the RGB of Carina in the further analysis.

The resulting analysis of RGB gradients for the remaining sample of dSphs is plotted in Fig. 6 in the same way as in Fig. 5 for the HB and listed in Tab. 2.

There is a wide variety of RGB morphological gradients: Sculptor, Sextans, Tucana, and Andromeda VI show strong and significant concentrations of the RRGB stars. Andromeda II does not show any change in its RGB morphology with increasing central distance.

In Andromeda I+III the blue RGB stars seem to be more concentrated. For Andromeda I this effect has a low K-S-test significance and can be attributed to small number statistics. Indeed, if we reanalyze the HB and RGB gradient strength in the same way as before, but separating at $60''$ instead of the core radius of $96''$, the result is consistent with no gradients in both the HB and the RGB. The apparent concentration of the blue RGB stars in Andromeda III is also very low and the statistical significance of a possibly existing gradient is also very low.

Because the dSphs, except for Carina, which is not considered here, do not contain a significant intermediate age population, we interpret red RGB stars as the more metal rich stars. A central concentration of the red RGB stars would thus imply a metallicity gradient.

The gradient strengths for the HB ($S[HB]$) and for the RGB ($S[RGB]$) are calculated for each dSph with the same radial binning. Therefore $S[HB]$ and $S[RGB]$ can be directly compared, independent of the actual field coverage within a dSph. We compare these two values in Fig. 7. All dSphs that exhibit a significant morphological gradient of the HB (Sextans, Tucana, Sculptor, and Andromeda VI) always show a significant concentration of the red RGB stars, too. There are no significant gradients in Andromeda II, III, and V within the covered area. Note that the result for Andromeda I (HB and RGB) may be unreliable. The nice correlation between RGB and HB gradient strength visible in Fig. 7 strongly suggests that metallicity is an important driver of the gradients.

7. The dSphs in the metallicity-HB-index diagram

A useful tool to compare HB morphologies and metallicities is a plot of metallicity vs. the HB index $\frac{B-R}{B+V+R}$ (Zinn 1993; Lee, Demarque, & Zinn 1994; Sarajedini, Chaboyer, & Demarque 1997). We calculate the HB index as described in the Section 4 for the eight dSphs. The number counts for the blue, variable, and red HB stars are listed in Tab. 3 together with the resulting HB index. We calculate the HB index for (a) the whole covered field and (b) in bins with the width of one core radius. We found in the case of Carina that we can not correct for the contamination of the RHB by RC stars. It is also impossible to derive a mean metallicity for the old HB forming population from the RGB only (what currently metallicities are based on), since this metallicity would be dominated by intermediate age stars. Putting Carina into the HB index diagram would be not representative for its HB forming population. Carina is therefore excluded from the investigation in this section.

7.1. The whole covered field

In Fig. 9 the mean HB-indices of the dSphs are plotted versus the mean metallicities with open circles. The metallicities are taken from the compilation of Grebel (2000) except for Tucana and some of the Andromeda companions. In Andromeda III, the spectroscopic mean metallicity suffers

from small number statistics (Guhathakurta et al. 2001); we adopt $[\text{Fe}/\text{H}] = -2.0$ dex (Armandroff et al. 1993). For Andromeda VI we derive in Sect. 7.2 $[\text{Fe}/\text{H}] = -1.6$ dex from our own analysis, and $[\text{Fe}/\text{H}] \sim -1.6$ dex for Tucana, as well. We also show the locations of the MW globular clusters with data from Harris (1996) (filled circles) and for the four Fornax dSph globular clusters based on data of Buonanno et al. (1999) (open stars). Isochrones for three different relative ages are super-imposed (Lee, Demarque, & Zinn 1994).

It turns out that the LG dSphs are not at the same location in this diagram as the single age population globular clusters of the MW. In particular the dSphs have redder HB morphologies than the mean of the MW GC system, but there are a few very red HB, metal-poor GCs in the MW that compare to the dSphs' HBs. If the HB morphology of the dSphs is indeed determined by age and metallicity only, the location in this diagram suggests that the dSphs may be systematically younger than the MW globular cluster system. On the other hand, there is evidence from deep main sequence photometry that the ages of nearby LG dSphs are comparable to the oldest MW GC clusters, e.g. shown for Sculptor by Monikiewicz et al. (1999); for Carina by Mighell (1997). The $[\text{Fe}/\text{H}]$ -HB-index diagram may not be the most reliable tool to compare relative ages of the dSphs, since many parameters such as mass loss, $[\alpha/\text{Fe}]$ and helium content affect age determinations. Additionally, the star formation histories of the dSph are by far more complex than that of the GCs.

In particular the content of α -elements in dSphs may be an important parameter for the HB morphology. A recent spectroscopic study by Shetrone, Côté & Sargent (2001) of RGB stars in the dSphs Draco, Ursa Minor, and Sextans suggests a decreased α -element abundance ($0.02 \leq [\alpha/\text{Fe}] \leq 0.12$) among these LG dSphs, compared to the Galactic globular clusters. At the present time, the total effect of α -element abundances in the stellar envelope on the HB morphology is not well understood. In general α -elements, especially oxygen, increase the opacity of stellar envelopes. For a fixed mass, stars with increased $[\alpha/\text{Fe}]$ will have lower surface temperatures and therefore will form redder HB stars (VandenBerg et al. 2000; VandenBerg & Bell 2001). Accordingly, one would expect that dSphs would form bluer HBs than the MW globular clusters. But an enhanced opacity of the stellar envelope, e.g. due to an increased $[\alpha/\text{Fe}]$, should lead to an enhanced mass loss during the RGB evolutionary phase. As a consequence, stellar populations with increased $[\alpha/\text{Fe}]$ might form lower mass HB stars with higher surface temperatures. In this case the reduced α -element content of the dSphs could explain the systematically redder HBs of the dSphs.

Nearly all globular clusters contain RGB stars that show abundance patterns that indicate deep mixing, while the amount of deep mixing stars can vary from cluster to cluster, as reviewed, e.g., in Kraft (1994). Some models and correlation exist that suggest that deep mixing may indeed be a second parameter in globular clusters (Sweigart & Catelan 1998; Cavallo & Nagar 2000). If deep mixing were an internal second parameter in dwarf spheroidals, one would expect different abundance patterns among stars with different radial distances to the dSphs' centers.

The five Fornax globular clusters are known to have very red HB morphologies compared to

their metallicity (Smith, Rich, & Neill 1998; Buonanno et al. 1999) and are located at similar positions as the dSphs in Fig. 9. According to Buonanno et al. (1999), however, most of the Fornax GCs have ages comparable to the MW GC system.

7.2. Radial dependence of the HB index and the metallicity

Table 3 contains the HB morphology indices of the dSphs for different radial bins. The HB morphological gradients detected above are also reflected in the radial dependence of the HB morphology index.

All dSphs observed with the HST have well observed RGBs in the luminosity where star by star metallicity determinations using fiducials are possible. In Sculptor the stars of the upper RGB are saturated and we cannot perform a star by star analysis here. An analysis of the mean color of the lower RGB was found to be too unreliable to obtain meaningful results. In Sextans and in Carina field star contamination would affect photometric mean metallicities. Since in Carina there is a dominant intermediate age population, the RGB color can not become translated into a metallicity, since age becomes an important additional governing parameter.

Tucana and Andromeda VI are the only two dSphs that have significant HB morphology gradients in this sub-sample, where we can derive star by star metallicities. To compare the location of different radial bins in the $[\text{Fe}/\text{H}]$ -HB-morphology diagram, we analyze the metallicity distribution. We use fiducials in the V,I color space (Da Costa & Armandroff 1990) and in the B,V filters (Sarajedini & Layden 1997) to transform the location in the CMD of RGB stars into a metallicity. In particular we use fiducials of the globular clusters M15, NGC 6752, NGC 1851, and 47 Tuc with metallicities of $[\text{Fe}/\text{H}] = -2.17$ dex, -1.54 dex, and -1.29 dex, and -0.71 dex according to the sample of Da Costa & Armandroff (1990).

The upper panels of Fig. 10 show the metallicity distributions for the inner and outer parts as well as for the whole covered field of Andromeda VI and Tucana. In the lower panels of the same figure the error-folded distribution of metallicities is shown. We assumed a general uncertainty of ± 0.05 dex in $[\text{Fe}/\text{H}]$ plus an additional photometric error folded with the dependence $\frac{\Delta[\text{Fe}/\text{H}]}{\Delta(B-V)}$ of the metallicity on the a star’s color.

From the $[\text{Fe}/\text{H}]$ distributions of Andromeda VI and Tucana we calculate the median as an estimate for the mean metallicities. Although the median is quite robust against outliers, we exclude stars with metallicities higher than -1.0 dex, which we consider to be field stars. Another source of contamination for $[\text{Fe}/\text{H}] \geq -1$ dex could be CH stars. Both for Tucana and Andromeda VI we derive a mean $[\text{Fe}/\text{H}] = -1.6$ dex. Note the bimodal metallicity distribution in Tucana. The derived $[\text{Fe}/\text{H}]$ for Andromeda VI is compatible with the result of Armandroff, Jacoby, & Davies (1999), but 0.3 dex more metal-poor than the result of Grebel & Guhathakurta (1999). Our analysis estimates Tucana to be 0.2 dex more metal-rich than the study by Saviane, Held, & Piotto (1996).

The visual inspection of the metallicity distributions of Andromeda VI and Tucana (Fig. 10) reveals that the ratio of metal poor and metal rich stars changes significantly for different radial selections. For Andromeda VI we derive metallicities of -1.55 dex and -1.7 dex for the inner and outer region, respectively. From Table 3 HB indices of -0.85 and -0.55 are obtained for the same regions. The metallicities of the inner and outer bins of Tucana are calculated to be -1.56 dex and -1.62 dex. The HB indices of the bins are -0.27 and 0.01 , respectively. It is worth mentioning that the strong RGB morphology gradients that we derived in section 6 for Tucana and Andromeda VI can be accounted for by a relative small difference in the mean metallicity.

7.2.1. Reality check

We will briefly discuss three points regarding the reality of the apparent gradient in the metallicity in Andromeda VI and Tucana and the influence of field star contamination:

1. Keck/LRIS spectroscopy of bright giants in four Andromeda dSphs (Guhathakurta et al. 2001) directly gives the contamination fraction from a radial velocity membership criterion. The only non-members found (M31 field giants and foreground Galactic dwarf stars) are invariably found well away from the center of the dSphs. In fact, the cross-identified stars in common between the HST star list and the Keck spectroscopy list does not contain even a single non-member - i.e. zero non-members out of a total of 34 cross-ID-ed stars in the four dSphs. The HST star-by-star metallicity estimates (for which we are considering contamination issues) are dominated in number by RGB stars fainter than those in the Keck spectroscopic sample, but this only means that the fractional contamination from foreground Galactic dwarfs will be even lower.
2. Contamination, both by foreground Galactic dwarf stars and M31 field RGB stars (halo or disk) tends to cause an apparent increase in the estimated $[\text{Fe}/\text{H}]$ of the population. Since contamination is bound to be greater in the outer ($r \geq r_c$) sample than in the inner sample, this goes the wrong way to explain the $[\text{Fe}/\text{H}]$ radial gradient that is observed.

7.2.2. The inner and outer bin in the HB-index- $[\text{Fe}/\text{H}]$ diagram

The location of the inner and outer bins of the two dSphs in the $[\text{Fe}/\text{H}]$ -HB-index diagram is plotted in Fig. 9. The positions of the inner and outer bins of the two galaxies in this diagram suggest that metallicity is the main parameter driving the HB gradient. According to the model of Lee, Demarque, & Zinn (1994) there is no *internal* second parameter required to explain the HB morphology gradients in these two galaxies. But taking into account the uncertainty of the HB morphology index (especially to mention the contamination of the HB by the RGB and its correction and the lack of direct RR Lyrae identification), an age spread of 2 Gyr in these two

galaxies can not be excluded.

7.2.3. *The bimodal metallicity distribution of Tucana*

The plot of Tucana’s metallicity distribution in Fig. 10 suggests a bimodal distribution; in fact that the multimodality exists in the inner and the outer bin, with similar peaks, supports the reality of this effect.

This multimodal metallicity distribution suggests that Tucana formed stars in two or more major events. In the previous section we demonstrated that there is no evidence for a significant age gradient in Tucana. Furthermore, the absence of carbon stars in Tucana (Battinelli & Demers 2000) as well as the absence of a red clump indicates that there is no significant intermediate age population. The star formation in Tucana therefore happened in a quite narrow age window at least 10 Gyr ago. Different radial distributions of the populations that formed in the different epochs are still visible at the present time by the morphological gradients in the RGB and the HB.

8. Global parameters governing the morphology gradients in the HB

To investigate the possible impact of environmental effects, we plot the gradient strength $S[HB]$ of the dSphs against their absolute magnitude M_V and against their deprojected distance to the nearest massive spiral galaxy (Fig. 8 a and b). The absolute magnitude and distances were taken from the compilation of Grebel (2000). As pointed out by Bellazzini, Fusi Pecci, & Ferraro (1996), one should keep in mind that the currently observed distance of the galaxy may not be representative of its orbit and the distance during the star forming episodes; the probability to find a satellite galaxy in its apogalactic orbit position is higher than at the pericenter. The whole sample of galaxies is quite inhomogeneous in gradient strengths and does not show a significant dependence of $S[HB]$ on the radial distance or the absolute luminosity.

The field coverage of our data compared to the radial extent of the dSphs in our sample varies a lot. But for each of our sample galaxies the data cover an area of at least $1.25 \cdot r_c$. We therefore redetermined $S[HB]$ for all galaxies taking only the central 1.25 core radii into account. This gradient strength will be called $S_c[HB]$. These new gradient strengths $S_c[HB]$ and their significance T_2 are listed in Tab. 4. Within this common central radius of $1.25 \cdot r_c$ the gradient strengths for the Milky Way companions and Tucana tend to become weaker (reflected by slightly increased $S_c[HB]$) than before and closely resemble the strength of the M 31 dSphs measured within the same core radius. The case of Andromeda V demonstrates that an insufficient field coverage may lead to completely different results. We expect that the HB morphology variations in the M 31 companions may become more pronounced and significant if a larger area of these galaxies were covered.

A new comparison of the $S_c[HB]$ parameters with the luminosity and distance to the nearest spiral does not reveal any significant correlations either. We therefore exclude the absolute luminosity and the present day radial distance from the nearest massive spiral as parameters governing the HB gradients within the restrictions of our sample.

9. Conclusions

We have compared the HBs of nine Local Group dSphs. The existence of a morphological gradient of the HB turns out to be a common, but not a defining, feature of dSphs. If there is a population gradient, the RHB or RC stars are always more concentrated than the BHB stars; there is no counter example in our sample. The main parameters governing the HB morphology are age and metallicity. There are other possible candidates such as stellar rotation, but there is no obvious mechanism that would systematically alter this parameter in the low-density environment of a dSph as a function of radius.

Increasing the helium abundance would lead to lower mass HB stars and would therefore foster the formation of bluer HBs (Lee, Demarque, & Zinn 1994). For the solar vicinity a correlation between metallicity and helium was found with $\Delta Y / \Delta Z \sim 3$ (Pagel & Portinari 1998). Increased $[\text{Fe}/\text{H}]$ should therefore be accompanied by an enhancement of $[\text{Y}/\text{H}]$ and might overall reduce the effect of metallicity on the HB.

Metallicity as one defining parameter for the HB morphology could produce morphology gradients through a much more efficient self-enrichment of the star forming gas in the central region of a dSph. The driver of the gradient could be the gravitational potential of the dSph which would either retain the star forming gas longer in its central regions, or retain both the gas and newly formed metals (Mayer et al. 2001). The correlation between the central concentration of red RGB stars (supposed to be metal-rich) and the concentration of red HB stars (also assumed to be metal-rich) in Fig. 7, supports the idea of a global metallicity gradient. Examples where metallicity is an important driver for the HB morphology gradients in our sample are Sextans, Sculptor, Tucana, and Andromeda VI. The location of the inner and outer bins of Andromeda VI and Tucana is consistent with a pure metallicity effect.

In contrast, age as a governing parameter of the HB morphology would support the idea that gas in the dSphs could be retained in the center of the dSphs for a significantly longer time than in the outskirts (Grebel 2000). In our sample there is no evidence that age is the dominant governing parameter for the HB gradients. At least in the Carina dSph age is a viable parameter that correlates with the gradient of the He-core burning stars, as indicated by the strongly concentrated intermediate age RC. It is very interesting that the HB in Carina does not show a gradient effect. But Carina is the only dSph in our sample that has a dominant intermediate-age population and its star formation history is not directly comparable to the remaining predominantly old dSphs.

The central concentration of the youngest stars has also been seen in Fornax and in the

transition type galaxy Phoenix (Stetson, Hesser, & Smecker-Hane 1998; Martínez-Delgado, Gallart & Aparicio 1999). One may consider the transition type galaxy Phoenix as an example of a progenitor of a dSph with a strong population gradient.

Overall, in this study we were able to find dSphs with indications of (a) metallicity gradients (Tucana, Andromeda VI, Sextans, and Sculptor) (b) no or weak gradients (Andromeda I, II, III, and V) and (c) age gradients (Carina). Our observations seem to confirm the picture that no two galaxies are alike, not even when they are of the same morphological type.

We found no significant evidence that the proximity to a massive galaxy influenced the formation of an HB gradient, in contrast to van den Bergh’s (1994) and Grebel’s (1997) correlation between a dwarf galaxy’s stellar content and its distance to the Milky Way or M31. The HB and RGB morphology gradient in Tucana is an interesting result due to the fact that this galaxy is not associated with any massive spiral galaxy. It also exhibits a multimodal metallicity distribution, indicative of multiple episodes of star formation. If this dSph was not close to a massive galaxy while it formed stars, environmental effects like tidal gas stripping or an external UV field from a nearby galaxy rather than an extragalactic UV field, could not have introduced the population gradient as far as the progenitors of the HB stars are concerned. Hence it looks as if the formation of population gradients in dSphs is a process that is caused by interior processes within a dSph or that is triggered by external events that occur independently of a nearby massive galaxy.

What could trigger or inhibit the formation of an HB gradient in dSphs? If the formation of a population gradient is the normal mode of dSph evolution it may, e.g., have been stopped due to collisions with intergalactic gas clouds in some galaxies. Such a collision may strip the remaining gas out of the evolving galaxy and end any further star formation. On the other hand an intergalactic cloud may have been captured by a dSph and caused a second star forming epoch, a scenario that is suggestive for Tucana. Yet the shallow potential of a dSph makes it difficult to keep intergalactic gas clouds bound (Hirashita 1999). Mac Low & Ferrara (1999) found that the amount of gas lost by dwarf galaxies during their star forming epoch depends on the luminosity of the star burst and on the parent galaxy mass. The strength of the star forming time may therefore have been influenced by the starburst itself.

There is also no evidence that the spatial scales on which the population gradients appear are correlated with the core radius of a dSph. The minimum scale on which a population gradient becomes evident can vary a lot. Gradients seem to become most evident at a field coverage of at least one or two core radii. On smaller scales gradients may disappear (e.g., Andromeda I). But the HB morphology gradient in Sculptor can be seen down to a radius of $4''$ ($2/3 r_c$) with a K-S-Test probability of 5 %. To obtain a measure of the scale length for existing morphology gradients requires a field coverage of order of the tidal radius, which is lacking for many galaxies at present. With a sufficient field coverage one could define core radii for the RHB and BHB populations and attempt to correlate them with a natural length scale of a dSph.

This work is partly based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions. The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation, the National Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation. The Oschin Schmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. The UK Schmidt Telescope was operated by the Royal Observatory Edinburgh, with funding from the UK Science and Engineering Research Council (later the UK Particle Physics and Astronomy Research Council), until 1988 June, and thereafter by the Anglo-Australian Observatory.

D.G. acknowledges financial support for this project received from CONICYT through Fondecyt grant 8000002, and from the Universidad de Concepción through research grant No. 99.011.025. J.H. is a Cottrell Scholar of Research Corporation and acknowledges their support. We would like to thank A. Burkert and J. S. Gallagher for helpful discussions.

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This preprint was prepared with the AAS L^AT_EX macros v5.0.

Fig. 1.— Demonstration of the influence of age and metallicity on the RGB morphology: We show isochrones (Girardi et al. 2000) for $z = 0.004$ and $z = 0.0004$ for ages of 6, 10, and 14 Gyr.

Fig. 2.— Digital Sky Survey images of the nine dSphs in our sample with the footprint of the covered field.

Fig. 3.— Color magnitude diagrams of all dwarf spheroidals in our sample. The blue and red horizontal branch stars, and the red clump stars in Carina are selected according to the boxes.

Fig. 4.— As an example for counting HB stars in the HST photometry where the red HB and the RGB merge, the luminosity function (LF) for all stars with $B - V \geq 0.4$ is shown. At the luminosity of the HB the LF is modelled by a linear function und subtracted from the total. The remaining HB stars form a clearly distinct peak above the zero count level.

Fig. 5.— Radial distributions of the blue (dotted line) and red (solid line) horizontal branch (HB) stars for all our sample dSphs. For Carina we plot in addition the distribution of the red clump stars with a dashed line. The selection of the population is made according to Fig. 3. For all of the Milky Way satellites a concentration of the red HB or the red clump stars (Carina) can be seen. The histogram bars represent the blueness index N_{HB} for the radii covered by the bars. The vertical line marks the core radius. The strong horizontal line outside the core radius indicates the mean HB ratio in the outer region, if more than two core radii are covered.

Fig. 6.— Radial distributions of the blue (dotted line) and red (solid line) part of the red giant branch (RGB) stars for all our sample dSphs. Due to the strong field star contamination we can not analyze the radial distribution of the RGB stars in the Carina dSph. The selection of the red and blue RGB populations is made according to Fig. 3. The histogram blocks and numbers have the same meaning as in Fig. 5.

Fig. 7.— Comparison of the gradient strengths S for the horizontal branch stars ($S[HB]$) and for the red giant branch stars ($S[RGB]$). Galaxies with $S[RGB] \leq 1$ show a central concentration of red RGB stars, while galaxies with $S[RGB] \geq 1$ have a central concentration of blue RGB stars. The gradient strengths for those galaxies with $S[RGB]$ slightly larger than 1 is still consistent with no gradient effects. There is a clear correlation between the gradients in these two populations: According to Tab. 3, Sex, Tuc, And VI and Scl have significant gradients both in the RGB and HB. And V has weak gradients, while And II and And III don't show significant gradients. And I suffers from low number statistics.

Fig. 8.— a) Dependence of the population gradient as indicated by the HB gradient index $S[HB]$ (see text for definition) on the absolute luminosity of the dSph. $S[HB] = 1$ corresponds to an equal distribution of the blue and red HB stars, while $S[HB] = 0$ would indicate the maximal concentration of the red HB stars. b) $S[HB]$ compared to the logarithm of the distance to the nearest massive spiral galaxy. Milky Way companions are plotted with open circles, Andromeda satellites with filled dots. The distant galaxy Tucana is plotted with the open rectangle. There is no obvious correspondence between these parameters.

Fig. 9.— The Local Group dSphs in the HB index – metallicity plot (open circles). The dSphs’ HBs appear systematically redder for a given metallicity compared to the Milky Way globular clusters (filled circles). This suggests the dSphs may be slightly younger than the GCs. The location of the Fornax globular clusters (open stars) in this diagram indicates they are more comparable to the LG dSphs than the MW globulars. For the two dSphs Andromeda VI and Tucana the mean metallicity and HB indices for the inner and outer regions are drawn with small circles and connected with a solid line. For these two galaxies the HB morphology gradient can be explained by pure metallicity effect.

Fig. 10.— Metallicity distribution of RGB stars in Andromeda VI and Tucana. We show the histogram of the $[Fe/H]$ distribution in the upper half: The dotted bars show the distribution of all stars, while the solid line counts stars within a core radius and the dashed line counts stars more distant than a single core radius. We derive for the inner and outer regions metallicities of -1.55 dex and -1.7 dex for Andromeda VI; -1.56 dex and -1.62 dex for Tucana. In the lower part of the diagrams show the normalized density distribution of the $[Fe/H]$ measurements folded by their errors for the same radial selections as for the upper panels. Note that the amplitude of these distributions does not reflect the number of stars. The radial $[Fe/H]$ gradients still come out very nicely. Even the bimodal $[Fe/H]$ distribution in Tucana is still present.

Table 1. Observing log

Galaxy	Telescope, Instrument	Filters	r_o ['] ^a	r_c ^a	r_t ^a	$1 - \frac{a}{b}$	Reference
Carina	CTIO 1.5m	C,R	25'	8.8' ^b	29'	0.33	Grebel et al. (2001)
Sculptor	CTIO 4m, BTC	B,R	30'	5.8' ^b	76'	0.32	Hurley-Keller et al. (1998)
Sextans	CTIO 4m, Mosaic 2	C, T ₁	40'	16.6' ^b	160'	0.35	Harbeck et al. (2001)
Tucana	HST, WFPC 2	F555W, F814W	1.7'	0.7' ^c	...	0.48	(HST archive)
And I	HST, WFPC 2	F439W, F555W	2'	1.6' ^d	13.3'	0	Da Costa et al. (1996)
And II	HST, WFPC 2	F439W, F555W	2.8'	1.6' ^d	17'	0.3	Da Costa et al. (2000)
And III	HST, WFPC 2	F439W, F555W	2'	1.3' ^d	6.2'	0.6	(HST archive)
And V	HST, WFPC 2	F439W, F555W	2'	0.5' ^e	...	0	(HST archive)
And VI	HST, WFPC 2	F439W, F555W	2'	1.3' ^e	...	0.23	(HST archive)

Note. — ^a r_o : radius covered by observations, r_c : core radius, r_t : tidal radius. ^b Irwin & Hatzidimitriou (1995)
^c Saviane, Held, & Piotto (1996) ^d Caldwell et al. (1992) ^e Caldwell (1999)

Table 2. Statistical significance of population gradients

Galaxy	horizontal branch			red clump			red giant branch		
	K-S [%]	T_2	$S[HB]$	K-S [%]	T_2	$S[RC]$	K-S [%]	T_2	$S[RGB]$
Carina	43	0.13	1.0	$5 \cdot 10^{-4}$	3	0.57	...	...	...
Sculptor	$1.8 \cdot 10^{-9}$	6.2	0.65	...	...	...	$5 \cdot 10^{-3}$	4.5	0.86
Sextans	0.5	2.6	0.57	...	...	...	$1.5 \cdot 10^{-4}$	5.3	0.81
Tucana	$5 \cdot 10^{-4}$	4.4	0.54	...	...	...	5	2.9	0.72
And I	44	2.6	0.37	...	...	...	49	2.9	1.3
And II	22	1.2	0.72	...	...	...	99	0.9	1.1
And III	33	0.9	0.71	...	...	...	24	0.5	1.05
And V	24	0.7	0.83	...	...	...	6	1.3	0.9
And VI	0.1	2.7	0.56	...	...	...	$8 \cdot 10^{-4}$	6.6	0.74

Table 3. HB morphology indices

Galaxy	#B	#V	#R	$\frac{B-R}{B+V+R}$
Carina	...	...	...	...
Sculptor ^a	353	243	299	0.06
I ^b	136	98	184	-0.11
II	139	89	98	0.13
III	19	7	8	0.32
IV	27	18	6	0.41
V	20	17	2	0.46
VI	5	10	0	0.33
VII	4	1	0	0.8
Sextans	102	24	237	-0.37
I	29	6	120	-0.59
II	58	13	104	-0.26
III	12	3	25	-0.32
IV	3	2	4	-0.11
Tucana	162	58	264	-0.2
I	48	23	133	-0.42
II	65	25	79	-0.08
III	37	7	36	0.01
IV	9	2	9	0
And I	91	88	1144	-0.8
I	88	85	1079	-0.8
II	3	3	31	-0.75
And II	140	55	923	-0.7
I	90	36	614	-0.7
II	50	19	247	-0.62
And III	78	81	552	-0.67
I	39	44	328	-0.7
II	34	31	196	-0.61
III	5	6	51	-0.74
And V	89	111	562	-0.62
I	19	25	169	-0.7
II	40	41	244	-0.63
III	29	42	153	-0.55
IV	3	3	8	-0.44
And VI	177	308	1749	-0.7
I	114	208	1445	-0.85
II	63	100	315	-0.53

Note. — ^a The first line of a dSph contains number counts for the whole covered field. ^b The numbers I, II, ... refer to number counts in the first, second, etc. radial bins.

Table 4. HB gradients in the inner $1.25 \cdot r_c$

Galaxy	T_2	$S_c[HB]$
Carina	1.4	1.8
Sculptor	2.1	0.81
Sextans	2.4	0.54
Tucana	2.0	0.66
And I	2.6	0.37
And II	1.6	0.65
And III	0.7	0.73
And V	0.3	1.2
And VI	2.7	0.56

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